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Effects of limb joint angles and body part vs. ground angles on horses' jumping style

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ABSTRACT
The aim of this study was to determine the effect of limb joint angles and body part vs. ground angles on jumping style in horses. Horses were categorized into groups based on selected criteria and characteristics. One-Way ANOVA was performed to determine the size effect of the different phases of jumping on limb joint angles and body part vs. ground angles. To study each jumping phase in more detail, the effect of each phase on the limb joint angles and body part vs. ground angles measurements was examined as a percentage across all groups. A correlation analysis was carried out to test the correlation between neck vs. ground angle in the takeoff phase and neck vs. ground angle in flight phase. However, the data were not reliable, so this correlation was disregarded and the horses were differentiated into four subgroups. As the presented angles are more affected by the takeoff and flight phases, these phases were studied in detail using correlation analysis. Only certain angles in all subgroups showed a reliable correlation with a probability ranging between 95% and 99.9%. This correlation was mainly observed in limb joint angles and body part vs. ground angles. We concluded that both forelimb joint angles and neck vs. ground angle during the takeoff and flight phases affect jumping style. We also noted the groups of horses with the most and least desirable jumping styles.

Keywords: Angular measure, Correlation, Jump phases, jumping qualities, Jumping style.
Article type: Research article.

INTRODUCTION
The increasing popularity of equestrian sports around the world requires a thorough study of the exterior features of horses participating in various disciplines in order to improve performance and the scientific basis for their selection (Rudak *et al.* 2019). Show jumping is one of the most popular equestrian disciplines, in which a rider and horse overcome a series of obstacles. In show jumping competitions, it is easy to see how horses overcome obstacles in different ways. You can observe the horse's endurance, the trajectory of the jump, how its body moves during the jump, and the points at which it takes off and lands. V. N. Dorofeev identified the high efficiency of jumping techniques in riderless horses and distinguished four phases: approach (bringing the hindlimbs towards the front limbs at the point of takeoff), takeoff (lifting the front limbs at an angle to the obstacle, with the hindlimbs fully extended), flight (the moment when the horse's center of gravity passes through the middle of the obstacle), landing (touching the ground with the front limbs while opening the hindlimbs). He noted that this phase structure is repeated in all horses, regardless of their age, sex, or breed (Dorofeev 1995). From a biomechanical perspective, a jump in equestrian sports is an exercise in which the motor task is to overcome a certain height and configuration

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of obstacle as a result of flight (Varnavsky 1984). Of course, many other factors affect the results of horses' performances in competitions, such as exterior, origin, and breed (Dorofeev 1984). However, all these concepts can be summarized as a jumping style. Therefore, a horse's jumping style can be defined as the way in which it overcomes an obstacle using its biomechanics, power, and jumping technique. A competition horse's career starts at a young age. Its development is affected by factors such as a calm ride, the right training approach, etc. There are many ways of evaluating young horses' ability to overcome obstacles. For KWPN competition horses, for example, a linear evaluation method is used, taking into account the following parameters when jumping: direction and speed of takeoff; technique of the front limbs, the back, the hindlimbs, reserve, elasticity, and accuracy (Bart Hendra 2011). It is the totality of these parameters that determines the style of the jump. However, the score given by the committee for a jump remains subjective and is based on qualitative parameters, which often results in inconsistent criteria being used by experts in the field. Therefore, a detailed biomechanical quantification of young horses during jumping would provide a better basis for accurately assessing their future athletic ability (Santamaria *et al.* 2002). The aim of this study was therefore to determine the effect of limb joint angles and body part vs. ground angles on horses' jumping style.

MATERIALS AND METHODS

The study was conducted on 100 Dutch half-bred stallions born in 2020, based on video footage from the initial breed survey (Emerlo 2022), in which the stallions' springarten jumping performance was evaluated. The original videos are the property of www.kwpn.nl. Video recordings captured key moments during the jump: approach, takeoff, flight and, landing. Angular measurements of the joints of the forelimbs and hindlimbs, as well as the neck, forelimb and hindlimb vs. ground angles were taken in each phase. Using the computer programme Uglomer (AngleMeasurer), markers were placed on specific points on the horse according to the method of French Scientists B. Langlois and J. Froidevaux (Langlois *et al.* 1978), as illustrated in Fig. 1. When measuring the body part vs. ground angles, it was found that the angles of the neck and forearm were always above or below the horizontal line in all phases of the jump. Therefore, they were labelled with a negative value when below the horizontal line and a positive value when above. The other angles were always above or below the horizontal line; therefore, no differentiation was needed, and these angles were labelled with positive values only.

The estimated statistical model of angles in different phases of the jump can be expressed as:

$$y_{ij} = \mu + \nu_j + \varepsilon_{ij}$$

where y_{ij} is the angle *j* in phase *i*, μ is the mean value, ν_j is the fixed angle, and ε_{ij} is the random error.

The primary data were analyzed and further calculations were performed using Microsoft Excel®. The studied horses were divided into groups based on their characteristics. A One-Way ANOVA with a 95% accuracy level was used to examine the effect of each jumping phase on the limb joint angles and body part vs. ground angles within each group, as well as the overall effect of all jumping phases on these angles. For a more-detailed research, we divided the horses into subgroups according to certain angle-related indicators and carried out correlation analysis of the selected indicators with all those studied. We described the correlations of reliable angles at $*p < 0.05$; $**p < 0.01$; $***p < 0.001$ and made further conclusions and suggestions.

RESULTS AND DISCUSSION

Analysis of the initial data revealed that body part vs. ground angles only vary at the neck and forearm (positive and negative). At the same time, combinations of these angles occur in different phases of the jump. Therefore, these angles were used to differentiate between the horses studied, given that the others are homogeneous. The neck vs. ground angle can vary in the following ways: below the horizontal line in both the takeoff and flight phases; below the horizontal line in the takeoff phase but above the horizontal line in the flight phase; above the horizontal line in the takeoff phase but below the horizontal line in the flight phase; above the horizontal line in both the takeoff and flight phases. The forearm vs. ground angle can be above or below the horizontal line in all phases of the jump. The approach and landing phases were not considered here, since the neck vs. ground angles are always above the horizontal line and the forearm vs. ground angles are always below this line in these phases. Thereby, eight groups of horses with these characteristics were obtained, as shown in Table 1. The effect of limb joint angles and body part vs. ground angles on the jump phases was established for each group through One-Way ANOVA with an accuracy of 95%. The percentages are displayed in Table 2. As presented in this Table, the effect of this factor is particularly significant for the angles in each group, with the exception of Groups 2 and 8. In these groups the jump phases do not appear to be affected by the arm vs. ground angle. The same angle had the lowest effect size in all other groups.

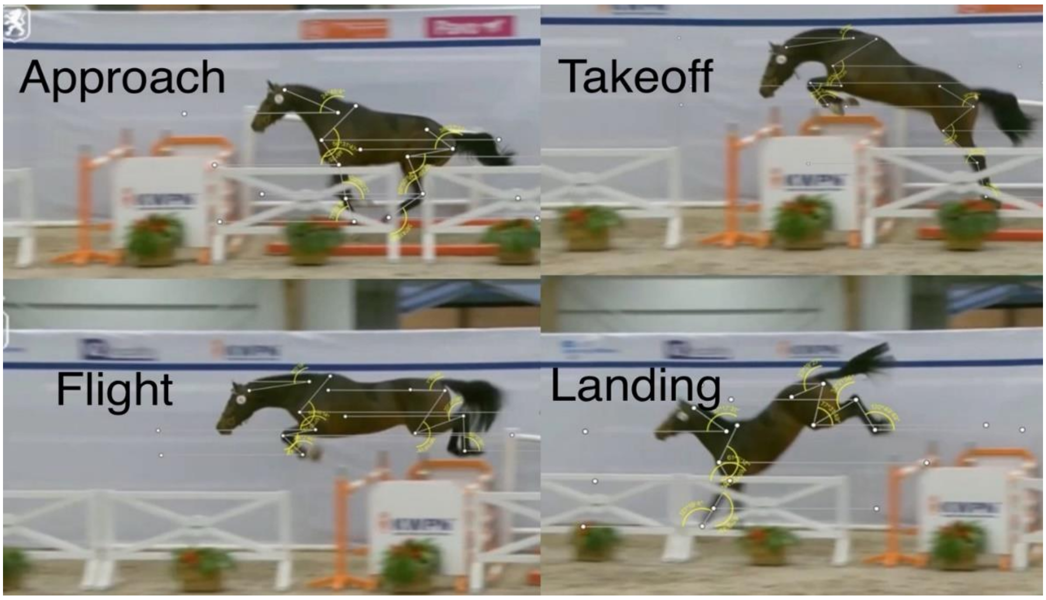

Fig. 1. Example of analysing angular measure in the different phases of a stallion's jump using still frames (https://www.kwpn.nl/database?Paard=P-646831).

It is important to notice that the forearms vs. ground angle demonstrates the highest effect size (up to 97.2) across all groups. Consequently, the index affects the jump phases the most. The elbow and carpus joint angles have similar values. This finding indicates that the forelimb joint angles are more susceptible to substantial changes during the jump phases. The analysis of each group separately has enabled the observation of relatively stable dynamics for each angle across all groups. This finding may be indicative of uniformity among the horses studied in each separate group, irrespective of variations in head count. To better understand each jump phase, the effect of limb joint angles and body part vs. ground angles was determined for each of the eight groups. The resulting percentages can be found in Table 3. As illustrated in this Table, the takeoff and flight phases are more substantially affected by the angles, particularly with regard to the neck vs. ground and forelimb vs. ground angles. The neck vs. ground angle presents the highest value both in takeoff (77.2%) and flight (73.4%) phases. The forearm vs. ground angle presents slightly lower values with 67.2 and 68.3%, respectively. This may be a consequence of the fact that these specific angles encompass a wider range both on the positive and on the negative side. The fore pastern vs. ground angle demonstrates the least effect in the takeoff phase with a value of 14.6%. This is due to the fact that the fore pastern position may vary during the training process. However, it is evident that the same angle is more significantly affected during the flight phase (30.7%). The shoulder joint angle has a value of 20.0% in the takeoff phase and 18.3% in the flight phase. The effect of this angle is attributable to its role in these two phases, given its impact on the takeoff direction, jump trajectory, and forelimb technique. With regard to the hindlimbs, the stifle joint angle is affected during the takeoff phase with a value of 19.2%, as it impacts the strength of the subsequent jump. The hip joint angle is affected during the flight phase (15.6%), as it impacts the jump elasticity and spine technique. The higher the hip joint angle, the lower the spine rounding, which in turn increases the probability of knocking down the rail.

As the phases under consideration exhibit the most significant effect from neck vs. ground angles, which can be positive or negative, it is essential to examine the correlation between the neck vs. ground angles during the takeoff and flight phases. A correlation analysis conducted between these indicators demonstrated the unreliability of the data; thus, the correlation between the neck vs. ground angles during the takeoff and flight phases may be disregarded. Therefore, neck angles should only be interpreted as being either above or below the horizontal line. Based on this and the fact that the forearm vs. shoulder angle can also be either above or below the horizontal line in all phases of the jump, all horses can be classified into four subgroups in each phase of the jump:

1. Neck and forearm below the horizontal line
2. Neck below the horizontal line, forearm above the horizontal line
3. Neck above the horizontal line, forearm below the horizontal line

4. Neck and forearm above the horizontal line

Table 1. Characteristics of the formed groups of horses.

Criteria	Group number and head count							
Croup No.	1	2	3	4	5	6	7	8
Head count	21	8	13	23	5	7	17	6
Neck vs. ground angles in degrees (M° ± m)								
Neck vs. ground angle below the horizontal line in both the takeoff	-6° ± 0.8 -10° ± 1.1	-9° ± 2.0 -9° ± 1.8						
Neck vs. ground angle below the horizontal line in the takeoff phase; above			-3° ± 0.7 5° ± 0.8		-1° ± 0.9 4° ± 2.0			
Neck vs. ground angle above the horizontal line in the takeoff phase; below the horizontal line in the flight				6° ± 0.8 -5° ± 0.7		6° ± 1.1 -7° ± 1.4		
Neck vs. ground angle above the horizontal line							10° ± 1.1 8° ± 1.2	9° ± 2.4 5° ± 0.8
Forearm vs. ground angles in degrees (M°±m)								
Forearm vs. ground angle below the horizontal		-4° ± 2.3 -8° ± 2.4			-13° ± 4.2 -8° ± 2.6	-12° ± 3.8 -15° ± 3.8		-5° ± 2.0 -13° ± 3.9
Forearm vs. ground angle above the horizontal line	9° ± 1.3 5° ± 0.8		17° ± 2.0 8° ± 1.2	14° ± 1.6 8° ± 1.0			14° ± 1.6 8° ± 1.5	

As the takeoff and flight phases are more affected by the neck vs. ground and forearm vs. ground angles, the correlation between these two angles in such phases was analyzed. As illustrated in Table 4, the correlation analysis of the neck vs. ground and forearm vs. ground is presented against all other angles studied in the takeoff phase. Analyzing Table 4, a moderate negative correlation is observed in Subgroup 1 between the neck vs. ground angle and the hock joint, recording values of -0.67 and -0.74 respectively, with a probability of $**p < 0.01$. This indicates that as the neck lowers to the ground in this phase, the hock joint opens wider, resulting in a jump directed upwards maintaining the altitude and high speed, thereby reducing the risk of knocking down the rail. In this subgroup, a moderate negative correlation can also be noted between the neck vs. ground angle and the shoulder vs. ground angle (-0.56) with a 95% probability. In other words, as the neck lowers, the shoulder vs. ground angle decreases, which allows for more freedom of movement along the flight trajectory, enabling the horse to jump with elasticity and a good bascule. The forearm vs. ground angle in Subgroup 1 does not show a significant correlation. In Subgroup 2, a correlation is predominantly observed between the forearm vs. ground angle and the other angles. The most significant correlation, with a 99.9% probability, reveals a moderate positive correlation between the shoulder joint angle (0.53) and the arm vs. ground angle (0.65). This means that as the neck lowers, the angle between the arm and the shoulder increases, thus extending the horse forward in flight and resulting in a flatter jump. Additionally, this subgroup exhibits a moderate positive correlation between the neck vs. ground and the forearm vs. ground angles, with a value of 0.43 (**$p < 0.01$), indicating that as the neck descends, the forearm rises, suggesting an optimal trajectory and minimal chance of knocking down the rail. Subgroup 3 shows a relationship solely between the forearm vs. ground angle and the elbow joint (-0.66), which is a moderate negative correlation with a probability of *$p < 0.05$. This means that as the forearm vs. ground angle increases, the elbow angle also increases.

Table 2. Effect of the limb joint angle and body part vs. ground angles on the jump phases for each group.

Limb joint angles and body part vs. body angles	Group No. 1	2	3	4	5	6	7	8
	Effect size of the factor (%)							
Shoulder	70.0	65.8	65.8	56.8	73.6	70.3	76.4	56.9
Elbow	94.4	88.1	95.5	96.0	94.6	94.3	90.5	92.7
Carpus	95.4	95.2	92.6	94.3	95.1	95.8	91.8	91.4
Hip	81.9	67.8	74.6	55.6	49.1	73.5	82.2	46.8
Stifle	88.2	89.5	86.2	79.8	80.2	81.6	84.2	75.4
Hock	84.7	82.4	83.6	74.2	65.8	72.7	78.9	66.0
Neck vs. ground	85.2	79.0	86.4	84.8	85.6	85.5	76.7	80.4
Shoulder vs. ground	80.8	75.2	76.6	82.5	78.4	75.3	79.5	75.0
Arm vs. ground	27.0	-	24.6	34.0	43.4	30.8	15.5	-
Forearm vs. ground	96.1	95.3	95.5	95.5	97.2	95.5	92.7	93.2
Fore paster vs. ground	68.6	68.3	56.1	55.0	62.0	67.1	57.1	61.9
Hip vs. ground	85.0	82.2	82.5	75.8	79.7	85.2	77.9	81.4
Hindquarter vs. ground	89.5	86.1	91.4	83.5	95.0	75.7	91.4	92.5
Gaskin vs. ground	81.5	86.2	86.6	70.4	80.7	70.4	80.9	68.5
Hind pastern vs. ground	84.1	58.7	88.8	78.8	90.0	78.2	85.5	81.5

Subgroup 4 displays moderate positive correlations of the forearm vs. ground angle with the shoulder joint (0.47), the wrist joint (0.33), the arm vs. ground angle (0.48), and the pastern vs. ground angle (0.60), as well as moderate negative correlations of the forearm vs. ground angle with the elbow joint (-0.32) and the shoulder vs. ground angle (-0.33). Given this scenario, the shoulder and wrist joints open wide, resulting in the horse jumping excessively upwards, with the trajectory appearing vertical rather than following a smooth arc relative to the obstacle. Thus, there is no forward movement, only upward movement. The situation is aggravated by the neck vs. ground angle, which is elevated above the horizontal line and exhibits a moderate negative correlation with the shoulder vs. ground angle (-0.61), indicating that as the neck height increases, the shoulder angle approaches the horizontal line, consequently raising the front limbs higher. The probability levels for this subgroup are presented in Table 4. Analyzing Table 5, a moderate positive correlation ($r = 0.51$, $p < 0.05$) is observed in Subgroup 1 between the neck vs. ground angle and the hock joint angle. This indicates that as the neck lowers during this phase, the hock joint opens wider, allowing the hindlimbs to follow a precise trajectory along a semi-circular path. Additionally, the forearm exhibits a moderate negative correlation with the elbow joint ($r = -0.69$, $p < 0.01$), meaning that as the forearm descends, the elbow joint angle increases. A similar pattern was observed in Subgroup 3 during the takeoff phase (Table 4). Subgroup 2 demonstrates a correlation solely between the neck vs. ground angle and the shoulder vs. ground angle, which is negative and moderate (-0.50) with a probability of

***p <0.001. A similar trend was evident during the takeoff phase in Subgroup 1 (Table 4), thus indicating a relationship between these angles as well. In Subgroup 3, a moderate positive correlation exists between the neck vs. ground angle and the shoulder joint angle (r = 0.65, $p < 0.05$). This suggests that as the neck elevates, the shoulder angle also increases, indicating that horses tend to lower their forelimbs early in preparation for landing. This behavior could adversely impact performance, as there is an increased likelihood of knocking down the rail. The situation is further complicated by a moderate negative correlation between the forearm vs. ground angle and the shoulder vs. ground angle (r = -0.64, $p < 0.05$). Horses in this subgroup tend to keep their forelimbs stationary beneath the body during the flight phase, which negatively affects jumping performance.

Table 3. Effect of limb joint angles and body part vs. ground angles on each jump phase for each group.

Limb joint angles and body part vs. ground angles	Effect size of the factor (%)			
	Approach	Takeoff	Flight	Landing
Shoulder	–	20.0	18.3	–
Elbow	–	18.0	–	–
Carpus	–	–	–	–
Hip	–	–	15.6	15.0
Stifle	–	19.2	–	–
Hock	–	–	–	16.7
Neck vs. ground	27.3	77.2	73.4	–
Shoulder vs. ground	–	20.1	17.8	–
Arm vs. ground	–	18.9	36.4	–
Forearm vs. ground	–	67.2	68.3	–
Fore pastern vs. ground	–	14.6	30.7	–
Hip vs. ground	–	–	–	–
Hindquarter vs. ground	21.9	–	–	–
Gaskin vs. ground	–	–	–	–
Hind pastern vs. ground	–	–	–	–

Note: an n-dash (–) is used to show that the factor has no influence

Table 4. Correlation analysis of neck vs. ground and forearm vs. ground against all other angles studied in the takeoff phase.

Limb joint angles and body part vs. ground angles	Subgroup							
	1. Neck and forearm below ground		2. Neck below the horizontal line, forearm above the horizontal line		3. Neck above the horizontal line, forearm below the horizontal line		4. Neck and forearm below the horizontal line	
	Neck	Forearm	Neck	Forearm	Neck	Forearm	Neck	Forearm
Shoulder	-0.22	-0.17	0.05	0.53***	-0.36	-0.12	-0.23	0.47**
Elbow	-0.16	-0.26	-0.24	-0.13	-0.29	-0.66*	0.09	-0.32*
Carpus	-0.14	-0.34	-0.07	0.12	0.09	-0.34	0.21	0.33*
Hip	-0.67**	0.19	-0.06	0.16	-0.46	-0.10	0.18	0.10
Stifle	0.11	0.06	-0.07	0.05	-0.13	-0.14	0.16	0.15
Hock	0.13	0.15	0.01	-0.18	-0.10	0.13	0.01	0.03
Neck vs. ground	1.00	-0.39	1.00	0.43**	1.00	0.27	1.00	0.05
Shoulder vs. ground	-0.56*	0.12	0.02	-0.20	-0.14	-0.37	-0.61***	-0.33*
Arm vs. ground	0.39	-0.24	0.11	0.65***	-0.23	0.44	0.11	0.48**
Forearm vs. ground	-0.39	1.00	0.43**	1.00	0.27	1.00	0.05	1.00

Fore pastern vs. ground	-0.07	-0.15	0.05	0.43**	0.10	0.02	0.21	0.60***
Hip vs. ground	-0.74**	0.35	-0.19	-0.13	-0.34	-0.11	-0.05	-0.05
Hindquarter vs. ground	0.04	-0.48	0.15	0.03	0.22	0.29	0.24	0.01
Gaskin vs. ground	-0.08	0.25	-0.17	-0.36*	0.07	-0.29	0.07	-0.01
Hind pastern vs. ground	0.16	-0.38	0.19	0.05	-0.26	0.05	-0.12	-0.14

Note: probability of *p < 0.05; **p < 0.01; ***p < 0.001

In Subgroup 4, a moderate negative correlation is observed between the neck vs. ground angle and the stifle joint angle (r = -0.38, $p < 0.05$). Consequently, as the neck elevates, the stifle joint angle decreases, indicating that the horses significantly tuck their hindlimbs. Moreover, considering the moderate negative correlation between the forearm vs. ground angle and the shoulder vs. ground angle (r = -0.41, $p < 0.05$) alongside the moderate positive correlation between the forearm vs. ground angle and the shoulder vs. ground angle (r = 0.50, $p < 0.01$), it can be inferred that horses in this subgroup extend their forelimbs significantly forward while lifting their forearm high above the horizontal line.

Table 5. Correlation analysis of neck vs. ground and forearm vs. ground against all other angles studied in the flight phase.

Limb joint angles and body part vs. ground angles	Subgroups							
	1. Neck and forearm below the horizontal line		2. Neck below the horizontal line, forearm above the horizontal line		3. Neck above the horizontal line, forearm below the horizontal line		4. Neck and forearm below the horizontal line	
	Neck	Forearm	Neck	Forearm	Neck	Forearm	Neck	Forearm
Shoulder	-0.27	0.28	-0.15	0.21	0.65*	0.36	0.10	0.22
Elbow	0.20	-0.69**	0.00	-0.14	0.58	-0.43	0.05	-0.05
Carpus	-0.06	-0.25	0.14	0.02	0.27	-0.34	-0.13	-0.16
Hip	0.10	0.31	0.20	0.00	0.16	0.07	-0.31	0.16
Stifle	0.36	-0.33	0.10	0.18	0.03	0.14	-0.38*	-0.07
Hock	0.51*	-0.06	0.06	0.23	0.07	0.12	-0.27	0.10
Neck vs. ground	1.00	-0.29	1.00	0.08	1.00	-0.05	1.00	-0.03
Shoulder vs. ground	-0.34	0.02	-0.50***	-0.24	-0.07	-0.64*	-0.07	-0.41*
Arm vs. ground	-0.03	0.50	0.10	0.13	0.27	0.44	0.11	0.50**
Forearm vs. ground	-0.29	1.00	0.08	1.00	-0.05	1.00	-0.03	1.00
Fore pastern vs. ground	-0.42	0.48	0.19	0.28	0.37	-0.20	-0.16	0.23
Hip vs. ground	-0.25	0.26	0.09	0.10	-0.10	0.40	-0.14	-0.09
Hindquarter vs. ground	0.44	-0.27	0.07	0.03	0.36	-0.14	-0.01	0.09
Gaskin vs. ground	-0.26	0.44	0.10	-0.04	0.08	0.13	0.04	-0.04
Hind pastern vs. ground	0.45	0.09	0.06	0.14	0.27	-0.13	0.08	0.16

Note: probability of *p < 0.05; **p < 0.01; ***p < 0.001

CONCLUSION

Based on the findings, it can be concluded that the jumping style of horses is significantly affected by the forelimb joint angles and the neck vs. ground angle during the takeoff and flight phases. This aspect has also been examined in Dorota Levchuk's work on the impact of jumping training on the jumping style of young horses in the early stages of training (Lewczuk *et al.* 2013).

Recommendations

Thus, horses with the characteristics of Subgroups 1 and 2 are the most suited for an optimal jumping style and performance during both the takeoff and flight phases. This corresponds to stallions in Group 1 (with the neck angle below the horizontal line and the forearm angle above the horizontal line during the takeoff and flight phases) and Group 2 (with both the neck angle and forearm angle below the horizontal line during those phases). Horses in Group 3 (with the neck angle below the horizontal line during the takeoff phase but above the horizontal line during the flight phase and the forearm angle above the horizontal line in both phases) and Group 5 (with the neck angle below the horizontal line during takeoff but above the horizontal line during flight and the forearm angle below the horizontal line in both phases) also exhibit desirable characteristics during the takeoff phase. Additionally, horses in Group 4 (with the neck angle above the horizontal line during takeoff but below the horizontal line during flight and the forearm angle above the horizontal line in both phases) and Group 6 (with the neck angle above the horizontal line during takeoff but below the horizontal line during flight and the forearm angle below the horizontal line in both phases) display preferred characteristics during the flight phase. Conversely, the jumping styles of horses in Group 7 (with both neck and forearm angles above the horizontal line during the takeoff and flight phases) and Group 8 (with the neck angle above and the forearm angle below the horizontal line during both phases) are deemed undesirable.

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